LASER SOUND GENERATION IN A WELD POOL

Nancy M. Carlson and John A. Johnson

Idaho National Engineering Laboratory
EG&G Idaho, Inc., P. O. Box 1625
Idaho Falls, ID 83415

INTRODUCTION

A welding machine requires three additional basic components for truly automated operation: sensors which detect physical properties of the weld; a model of the welding process which relates the controllable welding parameters, current, voltage, welding speed, etc., to the physical properties of the weld; and a control system which takes the signals from the sensors and converts them into a form which can be used for feedback control of the welding machine [1]. As part of a larger program to investigate all aspects of this problem, this study is concerned with the development of ultrasonic sensors to detect the physical properties of the weld.

Previous work [2,3] in this area used contact piezoelectric transducers to monitor the geometry of the molten pool and proved the capability of ultrasonic techniques to provide information about the welding process. However, several disadvantages of this contact system have led to the consideration of other methods of introducing and detecting ultrasound in the region of the weld pool. The first step in devising a noncontacting technique for sensing the welding process, sound generation, is being investigated. Ultrasound is generated by focusing the beam from a pulsed laser on a molten weld pool. This method has been used by many investigators to generate sound in a variety of circumstances [4,5]. In this study the generated sound is being detected using standard contact piezoelectric transducers, but that transducer will be replaced in future work with noncontacting sensors such as an electromagnetic acoustic transducer (EMAT) [6].

BACKGROUND

Ultrasonic sensing of the welding process with contact techniques has been successfully used for detecting the geometry of the molten/solid interface [2,3] and the presence of defects in solidified weld metal [7]. The molten/solid interface geometry can be detected with refracted shear waves using a contact piezoelectric transducer mounted on a lucite wedge positioned opposite the welding electrode. Ultrasonic sensing of the dynamic molten weld pool geometry can provide a process control input signal which can be used to alter welding parameters resulting in consistent welds with desirable qualities and reduced numbers of defects.

In these investigations, contact techniques using piezoelectric transducers provided good sensitivity and the desired spacial resolution. However, several disadvantages of this method were apparent during the investigation. A transducer mounted on a wedge or housed in a liquid-filled tire can be adversely affected by continuous exposure to heat. The search unit must be carefully positioned on the weld sample for alignment and coupling to be maintained. The data can be adversely affected by the surface roughness of the welding sample which causes poor coupling. In the pulse-echo method, the sound wave must traverse the high temperature regions around the weld twice, resulting in decreased signal amplitude due to thermal gradients [8] and increased attenuation [9]. The returning echo amplitude is also dependent on the impedance mismatch between the solid and liquid phase. This impedance difference is small, and the reflection is further reduced by the lack of a sharp interface [10]. All these factors present difficulties that may impact wide use of a contact ultrasonic sensing system for real-time weld inspection in an industrial environment.

A noncontact sensing system for monitoring the welding process is proposed to reduce many of the stated disadvantages of the piezoelectric pulse-echo method for determining weld quality. The complete system would consist of a pulsed laser beam, directed onto the weld pool, generating sound waves in the pool. These would travel through the pool to an EMAT for noncontacting detection. The received signal would contain information about the geometry of the pool which could be extracted and sent to the controller for interpretation and action. This paper will address the generation of ultrasound in actual and simulated weld pools, and the analysis of the A scans acquired by a piezoelectric transducer mounted on the solid metal near the pool. Future work will consider the use of an EMAT as a receiver in place of the piezoelectric transducer.

EXPERIMENTAL PROCEDURE

In the initial experiments, a laser beam was focused on stationary molten weld pools to establish if the technique can generate ultrasound of sufficient magnitude in molten metal to be received by a piezoelectric transducer. Figure 1 shows schematically the beam from a Q-switched, Nd-YAG laser directed at the center of the stationary weld pool. The laser pulse width is 15 ns and the energy per pulse is approximately 8 mJ, focused to a 1 mm spot size. The intensity is great enough to cause ablation of the material on the surface of the pool. The stationary weld pool is made on a 25.4 mm (1 in.) thick carbon steel using the gas tungsten arc welding (GTAW) process. The surface of the weld sample is ground to remove mill scale, thus providing a more uniform surface finish. A 5 MHz broadband transducer, mounted on a lucite wedge which is most sensitive to 45° refracted longitudinal waves, is centered 50.8 mm (2 in.) from the laser spot and coupled to the metal surface with couplant. The transducer is placed at this position to optimize the reception of the full vee 45° longitudinal wave. In addition this transducer is also sensitive to 23° shear waves. The welding electrode is positioned directly above the laser spot to assure that the laser beam will generate sound at the approximate center of the weld pool. The arc is initiated with a touch start and a stationary weld pool is formed. Digitized data are acquired before and during the formation of the weld pool using a CAMAC based LSI 11-73 work station [11].

Figure 2 shows two A scans from one weld. Before welding two large signals are observed corresponding to the full vee longitudinal wave at 45° and a mode converted shear wave at 27° as shown schematically in Figure 1. During welding these two signals each appear to split into two

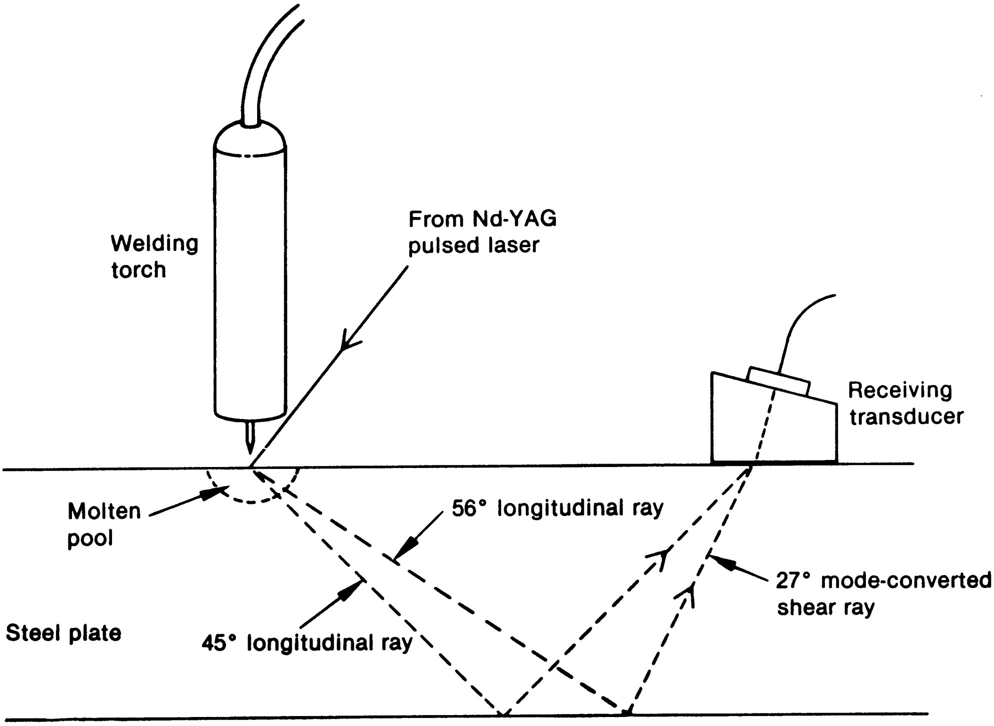

Fig. 1. Schematic of laser ultrasound generation in a weld pool.

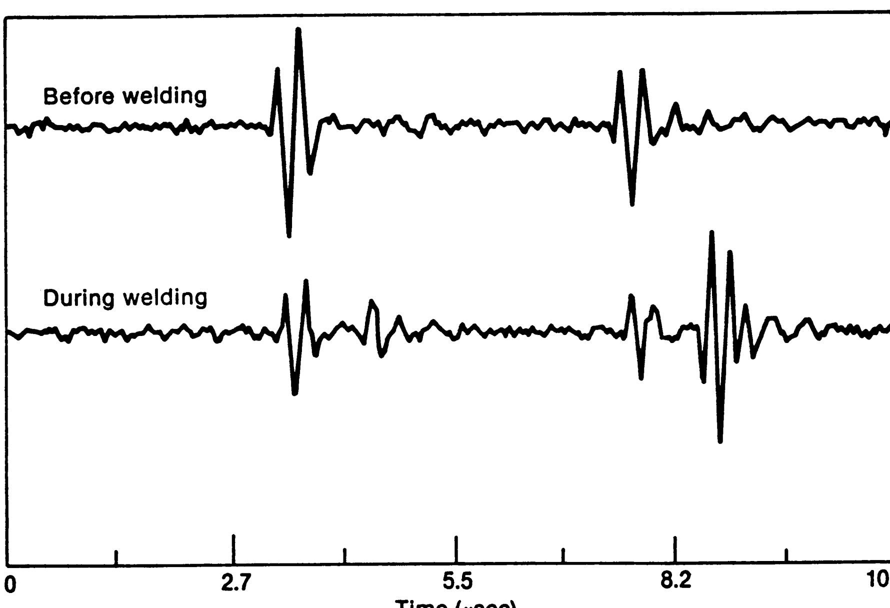

Fig. 2. A scans received before and during welding.

signals. Clearly the formation of the weld pool has affected the transmission of sound from the laser source at the surface to the receiving transducer. Thus the received signal contains information about the weld pool which may be useful for feedback control of the welding process. However, a complete understanding of the signals requires a knowledge of the many complicated effects that the weld pool can have on the sound field, including temperature gradients, the shape of the molten/solid interface, the motion of the pool surface, and mode conversion at the interface.

A problem in the experiment was a lack of consistency in the weld pools, even for those made with the same parameters. When the welds were destructively examined, the interface geometries of most of the pools were quite irregular, making analysis of the transmission of ultrasound through the interface extremely difficult. However, A scans acquired from several pools with a spherical geometry had two significant reflections present in each A scan. A more controlled experiment to simulate the weld pool experiments was designed which eliminated the variations in the pool geometry and the effects due to thermal gradients and pool surface motion.

For the simulated weld pools, a sample of 25.4 mm (1 in.) thick carbon steel was prepared with a series of 5 machined dimples. The dimples were made using a ball-end mill of a 6.35 mm radius. The depth of the five dimples varied in 1 mm increments from 2 to 6 mm. The top-surface radii of the respective five dimples varied from 4.63 to 6.35 mm. Glycerine was selected as the most appropriate liquid for simulating a molten weld pool without causing a personnel hazard during laser ablation. It was necessary to mix black ink with the glycerine to improve the light absorption. The five machined dimples were filled with the blackened glycerine to a level even with the surface of the steel sample. The laser beam was focused to 1 mm spot size using a 300 mm lens and directed to the simulated pool by a mirror. Laser power was manually increased to achieve ablation resulting in the generation of pressure waves in the pool. The required energy was approximately 8 mJ/pulse. Data were acquired both with the laser operating in the repetitive mode with a 10 Hz repetition rate and in a single shot mode. Figure 3 shows the beam focused at the center of the glycerine-filled 6 mm dimple. The sound is received by the same 5 MHz piezoelectric transducer.

Data were collected at each of the pool depths using two different Nd-YAG lasers run at both a 10 Hz repetition rate and in the single shot mode. The A scans received from the simulated weld pools of the same depths were comparable. These data when compared to actual weld pool data of similar depth pools indicated that the signals are dependent on the geometry of the pool.

RESULTS

The analysis of laser generated sound started with the most straight forward case - sound waves produced by the laser spot ablating a solid metal surface and propagating over an all steel sound path. A program [12] to calculate Green's functions using the generalized ray theory developed by Pao and his collaborators [13] was used to determine the time of arrival, propagation mode, and displacement amplitude of both the horizontal and vertical components of the sound front. The transit times and propagation modes calculated by Green's function were compared to the arrival times observed in the laser generated sound acquired from

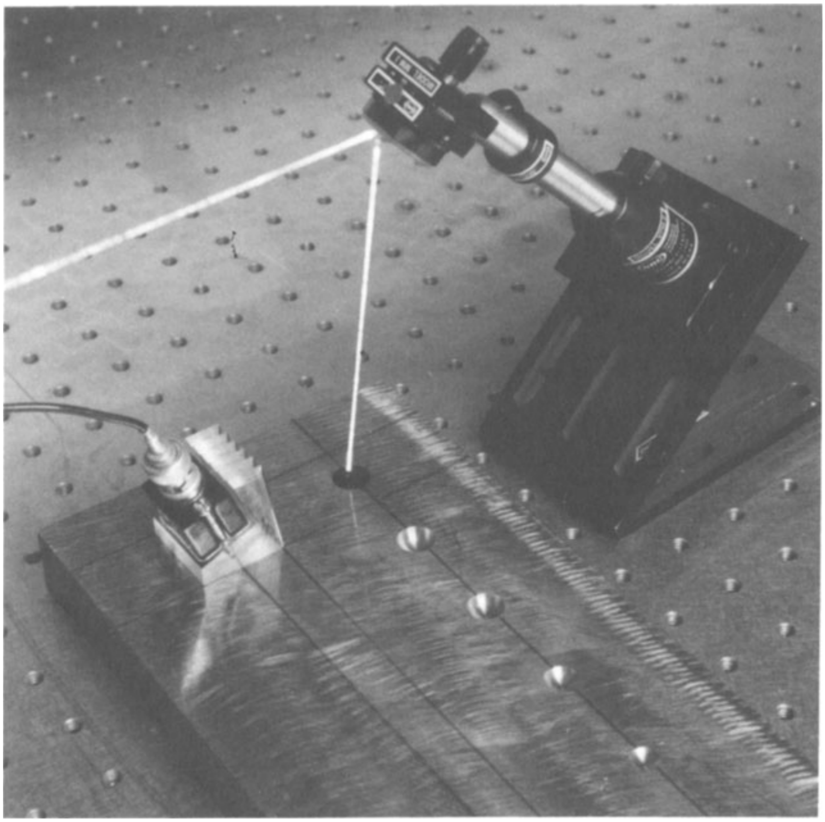

Fig. 3. Laser sound generation in a 6 mm deep dimple simulating a weld pool.

the carbon steel sample. In this case the transducer receives both compressional and shear stresses radiating from the focused laser spot ablating the steel.

Figure 4 compares the vertical component of the displacement vector of the Green's function and the actual all solid steel sound path data and indicates the mode of propagation of each signal. There is good agreement between the data and the arrival times calculated by Green's function. The differences in the relative amplitudes are due to the directional sensitivity of the wedge-mounted piezoelectric transducer.

To compare these data in Figure 4, 4.39 μs was subtracted from the arrival time of the signals to correct for sound propagation in the lucite wedge. The 4.39 μs is the time required for a longitudinal sound wave to propagate along a 12 mm lucite sound path at the longitudinal velocity of 2.73 mm/μs. This time is exact only for longitudinal waves at 45° and shear waves at 23°. Other wave modes and angles have slightly different transit times through the lucite.

Some of the sound propagation modes are not supported in liquid. The modes of sound arrival that will be affected by the presence of the liquid pool are the modes with an initial shear wave leg and the Rayleigh wave. For any of these waves to occur in the presence of a liquid pool, mode conversion must occur at the solid/liquid boundary to generate the

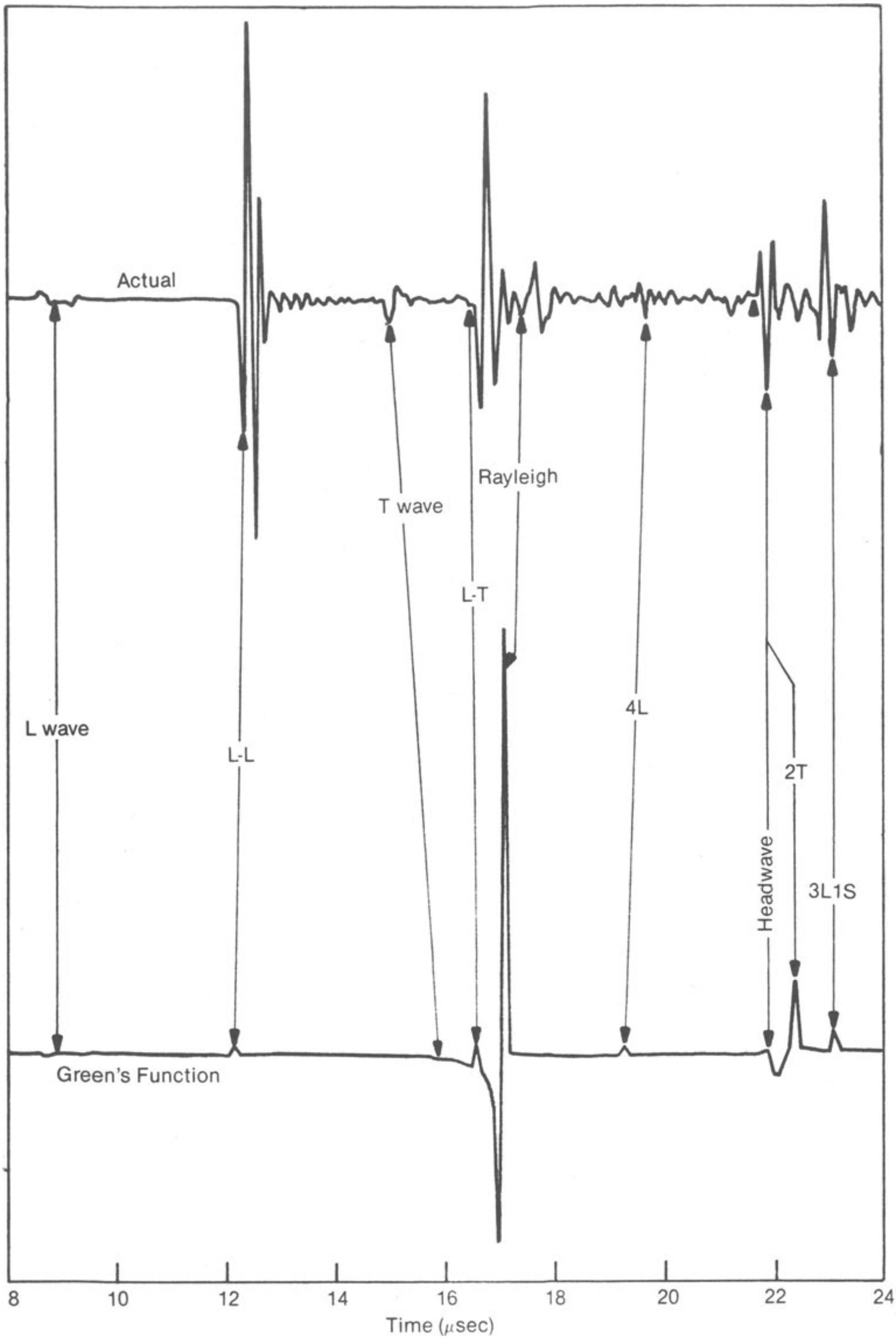

Fig. 4. All steel sound path data compared to Green's function.

necessary mode. For the greatest pool depths, 6 mm and 5 mm, the angles between incident rays from the center of the surface and the liquid/solid interface are nearly 90° and little mode conversion is expected. However, for the 2 mm deep dimple, it can be shown mathematically that the critical angle of 36.6° necessary for propagating a surface wave at the liquid/solid boundary can be achieved by a ray propagating from the center of the pool. However, the waves are not plane waves and more complicated interactions can be expected at the interface.

Another consideration in the case of a liquid pool is that the sound wave can have multiple paths in the liquid. The case of most importance is a triple path in liquid. The signals from the multiple glycerine paths must be considered as the signals can occur during the time window selected for data collection. To confirm the arrival times of signals received when the liquid pool is present, a ray tracing computer code was written that calculates the path of rays originating from the pool and reflecting, refracting, or mode converting at the three interfaces (solid/liquid interface, top and bottom of the part).

The 4 mm deep dimple provides simulated data that can be compared with an actual spherical weld pool 3.8 mm deep. Figure 5 shows the photomicrograph of the actual weld pool and the A scans of the simulated and actual welds. The A scans are received from the 4 mm dimple and actual weld with the transducer placed 50.8 mm from the center of the 1 mm focused laser spot ablating the pool. When comparing the A scans from the simulated pool with the actual weld pool in Figure 5, the arrival times differ by 0.4 to 1.1 µs. This is the result of the velocity differences between glycerine at 1.92 mm/µs and liquid steel at 3.4 mm/µs and less at higher temperatures.

The ray tracing computer code is used to determine the source of the signals in the simulated weld pool. The signal that arrives at 10 µs is a ray with an incident angle of 30.37° in the pool that refracts directly on the first half vee to the top steel surface as a longitudinal wave at 85.5°. The signal at 13.6 µs is the 45.65° full vee refracted longitudinal wave. The signal at 17.4 µs is due to a shear wave generated at the molten/solid interface that mode converts to a longitudinal wave at the bottom metal surface. The multiple reflection of this wave with three legs of glycerine travel occurs at 21.6 µs. A longitudinal wave that refracts at 57.75° and mode converts to a shear wave at 27.49° arrives at 17.8 µs at the same arrival time as the longitudinal-longitudinal wave with three legs of travel in glycerine. Five of the six signals in the 16 µs window can be accounted for by use of the ray tracing field code. The signal that occurs at 18.3 µs occurs in all 4 mm deep simulated weld data of a spherical geometry although the amplitude of this signal is quite variable. The explanation of this signal has not been established by use of the ray trace computer code. A possible explanation is that a wave may convert to a surface wave at the liquid/metal interface and propagate as a surface wave along the top free boundary but the mechanism for such a conversion is not clearly understood.

In comparing the simulated data and the actual weld pool data, the main modes of propagation are examined first. The full vee longitudinal wave and the longitudinal wave which mode converts to a shear wave at the bottom surface are the largest signals in the two A scans in Figure 5. (The sound paths of these two main modes of sound propagation were shown on Figure 1.) The full vee longitudinal signal is observed at 12.5 µs in the actual weld and at 13.6 µs in the simulated weld. The mode-

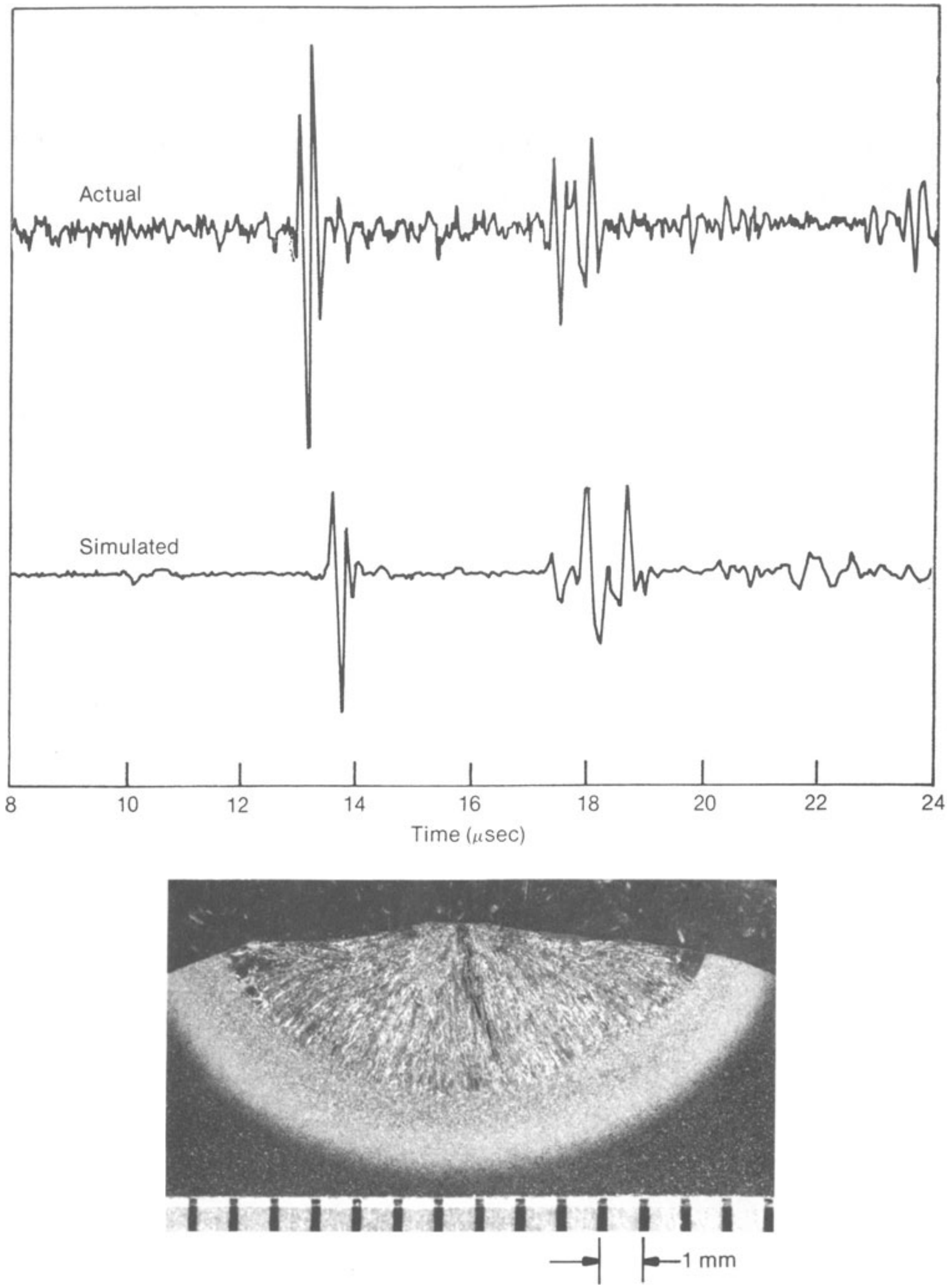

Fig. 5. Micrograph of a 4 mm deep weld with acquired data from the actual weld spot and a simulated weld pool.

converted longitudinal wave and a full vee longitudinal wave with three multiples in glycerine both arrive at approximately 17.4 μs in the actual weld and at 17.8 μs in the simulated data. The signal at 17.9 μs compares with the unexplained signal occurring at 18.3 μs in the simulated weld pool data. The signal that occurs between 22.9 and 23.5 μs occurs at the appropriate time for the headwave but the mechanism for the generation of surface longitudinal wave is not clear. A finite element field code is being used to determine the source of this signal and the signal at 18.3 μs in the simulated data and at 17.9 μs in the actual weld data [14].

CONCLUSIONS

Ultrasound can be generated in a noncontacting manner by a Q-switched Nd-YAG laser ablating the surface of the molten weld pool. A simulated glycerine-filled weld pool can be used to generate signals like those received from the actual weld pool. The source of most of these signals is confirmed with the ray tracing computer code. A predictive finite element field code is also being utilized to confirm the pressure and shear wave propagation and to determine the source of signals not yet understood. The signals are dependent on the pool geometry and indicate the depth of the pool based on the results obtained from these feasibility tests. Because of the signal dependence on the pool geometry, the received signal can provide input to a closed-loop system as to the appropriateness of the pool geometry and depth produced by the selected welding parameters.

A first step toward a noncontacting ultrasonic sensing system is shown to be feasible for stationary weld pools using conventional ultrasonic transducers. For the system to be noncontacting, the receiving sensor must also be replaced by a noncontact sensor. Electromagnetic acoustic transducers (EMATS) are the proposed candidates for this sensor. The EMAT will need to operate in the 2.25 MHz or higher range to achieve the spacial resolution necessary to determine the pool geometry and pool depth. Laser-generated sound received by an EMAT will provide a noncontacting sensing technique for frequencies of 2.25 MHz or less that can be used in a production welding environment.

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REFERENCES

1. J. A. Johnson et al., "Automated Welding Process Sensing and Control," to be published in the Proceedings of the 2nd International Symposium on the Nondestructive Characterization of Materials.

2. N. M. Carlson and J. A. Johnson, "Ultrasonic Sensing of Weld Pool Penetration", to be published in Welding Journal.

3. N. M. Carlson and J. A. Johnson, "Ultrasonic Detection of Weld Pool Geometry," Review of Progress in Quantitative NDE , 6B, D. O. Thompson and D. E. Chimenti, ed., New York: Plenum Publishing Corp., 1987, pp. 1723-1730.

4. T. G. Muir, C. R. Culbertson, and J. R. Clynch, "Experiments on Thermoacoustic Arrays with Laser Excitation", JASA 59, 1976, pp. 735-743.

5. R. J. Dewhurst, D. A. Hutchins, and S. B. Palmer, "Quantitative Measurements of Laser-generated Acoustic Waveforms", J. Appl. Phys. 54 (1982) pp. 4064-4071.

6. D. Hutchins, J. Hu, and K. Lindgren, "A Comparison of Laser and EMAT Techniques for Noncontact Ultrasonics," Materials Evaluation 44, (September 1986) pp. 1244-1253.

7. J. A. Johnson and N. M. Carlson, "Weld Energy Reduction by Using Concurrent Non-Destructive Evaluation," NDT International, 19, 3, (June 1986) pp. 190-196.

8. L. A. Lott, J. A. Johnson, and H. B. Smartt, "Real-Time Ultrasonic Sensing of Arc Welding Processes", Proceedings of the Symposium on Nondestructive Evaluation Application and Materials Processing, American Society for Metals, Metals Park, Ohio, 1984, pp. 13-22.

9. E. P. Papadakis et al., "Ultrasonic Attenuation and Velocity in Hot Specimens by the Momentary Contact Method with Pressure Coupling, and Some Results on Steel to 1200°C, JASA 52, pp. 850-858, (1972).

10. W. Kurz and B. Lux, Translated from Archiv f.d. Eisenhuttenwesen 39, 521-530 (1968). Available in English from Henry Brutcher Translations, ASM, Metals Park, Ohio as HB No. 7528.

11. J. A. Johnson, B. A. Barna, L. S. Beller, S. C. Taylor, and J. B. Walter, "CAMAC Based Ultrasonic Data Acquisition Workstation," to be published in Materials Evaluation.

12. N. N. Hsu, "Dynamic Green's Functions of an Infinite Plate - A Computer Program", National Bureau of Standards Report NBSIR 85-3234, August 1985.

13. Pao, Gajewski, and Ceranoglu, "Acoustic Emission and Transient Waves in an Elastic Plate", JASA 65, pp. 96-105, 1979.

14. J. A. Johnson, "Modeling of Laser Ultrasound Generation in a Weld Pool," included in these proceedings.